SINGLE-CHIP CONDENSER MINIATURE MICROPHONE WITH A HIGH SENSITIVE CIRCULAR CORRUGATED DIAPHRAGM

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ABSTRACT

A novel single-chip condenser miniature microphone with a circular corrugated diaphragm for residual stress releasing has been proposed, fabricated and tested. The condenser microphone consists of a rigid single-crystal backplate and a flexible circular corrugated diaphragm using induced couple plasma(ICP) etching. An electrostatic-structural coupling finite element analysis(FEA) was performed for design optimization. A sensitivity of 40mv/Pa up to 15KHz has been achieved under a low bias voltage of 14V, which is among the best in the presented reports.

INTRODUCTION

Over the last two decades, extensive efforts have been devoted to development of silicon micromachining miniature microphones[1,2]. Miniature microphones have superior performance in hearing aid, detectaphone, ultrasonic and precision acoustic measurement. Large miniature microphone array can also be realized with micromachining technique. In all these areas, silicon miniature microphone seems to be very promising.

Most miniature microphones presented are based on the capacitive detection principle because of the flat frequency response, small size, high signal-to-noise ratio and low power consumption[2-4]. However, the sensitivities of these diaphragm-based condenser transducers are determined by the diaphragm flexibility, which is greatly reduced by the residual stress in the diaphragm owing to the stress stiffening effect[3-5]. The typical sensitivities of condenser microphones were several mv/Pa, which were not sufficiently high for many applications. A good method for releasing the residual stress is the application of corrugated diaphragm[4,5]. The first corrugated diaphragm for condenser microphone applications was investigated by P.R. Scheeper[5]. Later, Q. Zou presented a single-chip condenser microphone with square corrugated diaphragms[4]. It was shown that corrugations can considerably increase the mechanical sensitivity of the diaphragm with equal size and thickness.

Numerical simulation results have shown that the sensitivities of circular corrugated diaphragms were several times larger than their square counterparts[6,7]. However, the structures must be redesigned to favor the single-chip approach. For the first time, a single-chip condenser miniature microphone with a high sensitive circular corrugated diaphragm was proposed and developed. The fabrication process revealed high yield, allowing a low cost production of high performance microphones capable of on-chip integration of signal processing electronics.

STRUCTURE AND FABRICATION

The diaphragm-based structures can be realized in one single chip by use of sacrificial layer etching(SLE). In the SLE process, the sacrificial layer should be etched through holes leaving a freestanding structure. To prevent the etchant from attacking structures and electronic components on the front side, the etch procedure should not take too much time. In this consideration, a large amount of access holes are required. In fact, these holes also serve as acoustic holes that can reduce the acoustic resistance of air gap and improve the high frequency performance of the microphone. To maintain the integrity of the backplate, the corrugations must not be self-closed. Therefore, continuous flat "bridges" appears on the diaphragm (as shown in Figure 1), which makes these novel corrugated diaphragms different from those achieved by bonding approach.

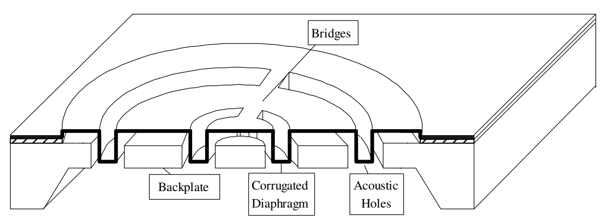

Figure 1. *A schematic view of the condenser microphone with a circular corrugated diaphragm*

The process starts with a double side polished N-type (100) silicon wafer. The major fabrication steps are shown in Figure 2, and described as follows:

1. Masking layers of thermal oxide and low-pressure chemical vapor deposition(LPCVD) of silicon nitride (Si_3N_4) are followed by patterning of the back windows for back chambers. A two-step anisotropic etching of bulk silicon is carried out in KOH aqueous with ultrasonic agitation to achieve uniform distribution of groove depth on the whole wafer. The back windows are etched to a depth of 370μm using a KOH solution, leaving a single crystal silicon membrane of 30μm[8].

2. Grooves are patterned and etched to the design depth on the upper side of the wafer using deep reactive ion etching(DRIE)-ICP. After the masking layer is removed, a thermal oxide of 0.5μm is formed as an insulating layer.
3. The backplate electrodes are coated with highly insulated silicon nitride to prevent the electric leakage, after patterning of the thermal oxide.
4. A LTO of 0.5μm together with a PSG of 2μm are deposited and annealed as the sacrificial layer. Small supports as well as sacrificial layer are patterned and etched in buffered HF solution.
5. The sandwich layer of the diaphragm, including phosphorus-doped polysilicon at the bottom (0.5μm) and LPCVD silicon nitride (0.1μm) at the top of the diaphragm are deposited and patterned with RIE.
6. The contacts of the diaphragm electrodes and the substrate are patterned and a 1μm-thick aluminum is evaporated, patterned and metallized.
7. Finally, the back windows are further etched by RIE technique until the bottom of the corrugations appears, then the sacrificial layer is etched in BHF with the upper side protected by a thick photoresist layer. The fabrication process is completed by the release of the diaphragms by rinsing in deionized water (DI) and IPA, then the whole structure is dried in air.

This process is simple, efficient and has good reproducibility, and the structure materials are compatible with standard CMOS process. Integration of signal conditioning circuitry is expected to make a complete micro-acoustic system[10].

MODELING AND SIMULATION

The open-circuit sensitivity of a condenser microphone is defined by the product of the diaphragm mechanical sensitivity and the bias voltage applied across the capacitor gap. Increasing the bias voltage can result in higher open-circuit sensitivity. However, the microphone diaphragm collapses to the backplate at a certain voltage. The maximal bias voltage is a principle design object for certain applications, which is in close relation to the static deflection and the mechanical sensitivity.

For microstructures, mechanical forces developed by electrostatic fields can be significant enough to deform structures. The deformation can also affect the electrostatic field, hence requiring a coupled-field solution. A coupled-field analysis is an analysis that takes into account the interaction between two or more fields of engineering. The simulation is carried out using the direct method, which involves just one analysis that uses a coupled-field element type containing all necessary degrees of freedom. To get the optimum values of the design parameters, an electrostatic-structural coupling FEM analysis was performed using ANSYS/Multiphysics 5.7.1.

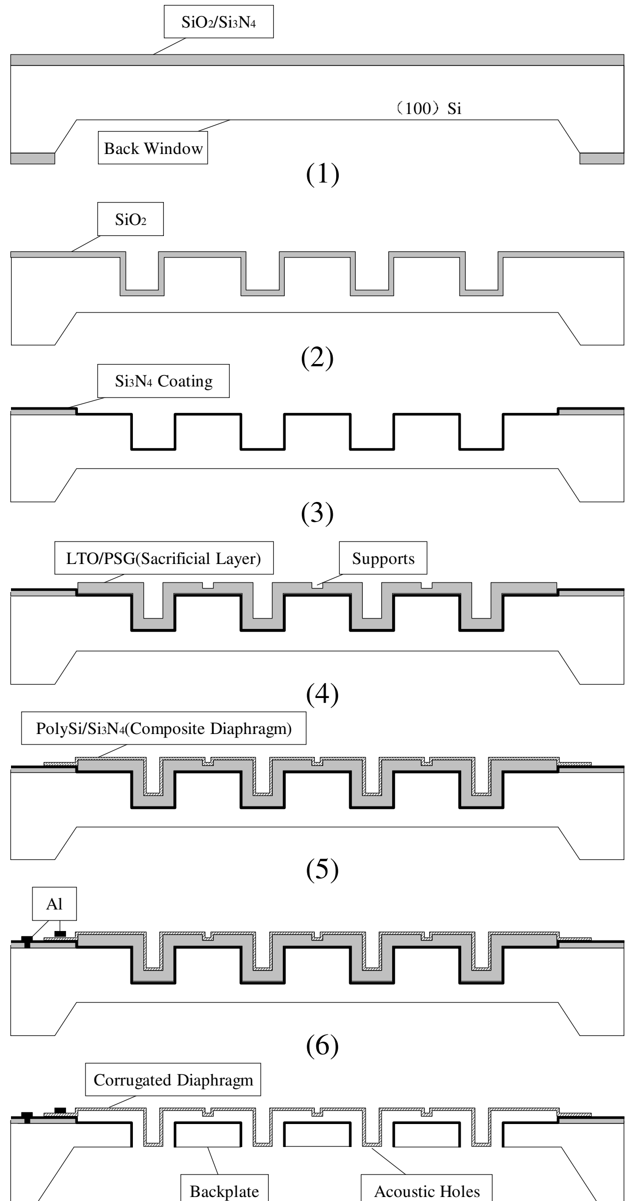

Figure 2. *Schematic representation of the microphone fabrication process*

Simulations performed using FEA have shown that the corrugated diaphragms having initial tensile stress exhibit a small deformation under zero pressure and bias voltage. The zero-pressure offset distribution of the circular corrugated diaphragm under a bias voltage of 5V is shown in Figure 3, with a close-up detail of central displacements in Figure 4. Note that the center portions do not remain flat because of the non-uniformly distributed internal stress, which does not occur for the flat diaphragm. For a planar diaphragm, the internal tensile stress is in-plane, giving rise to in-plane forces. The result of this internal tensile stress is to increase the rigidity of the planar diaphragm, which is so called "stress stiffening" effect. For a nonplanar diaphragm, the redistribution of internal tensile stress is non-uniform. The resulting forces do not remain in-plane due to this non-uniform stress distribution. These out-of-plane forces generate bending moments, causing the diaphragm to deflect[6].

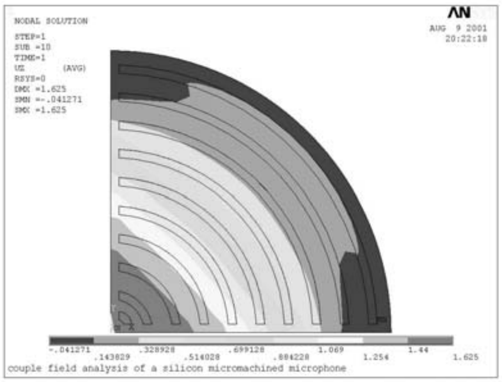

Figure 3. *The zero-pressure offset distribution*

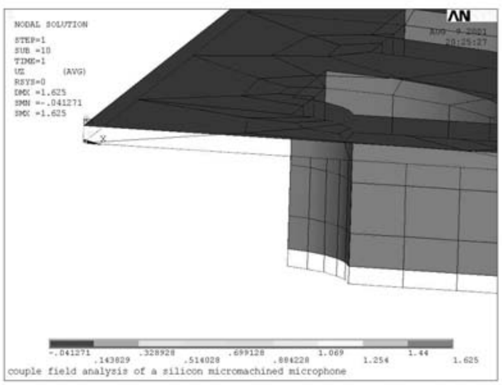

Figure 4. *The offset deflection of center areas*

The offset/bending direction of a corrugated diaphragm depends on the corrugation layout. For circular corrugated diaphragms, the offset deflection of center areas is “up”, that is, popping away from the backplate, while the squared types take the opposite direction[6,9]. Although zero-pressure offset is normally unwanted, the upside offset is desirable for diaphragm releasing and can greatly increase the deflection range.

The capacitor always works under a DC bias voltage. In this simulation, the fact that the electrostatic force is not distributed uniformly across the diaphragm was taken into account. A typical relation between the central deflection and the bias voltage of the circular corrugated diaphragm is shown in Figure 5. This curve can be naturally divided into four regions. In the first linear region for small bias voltages, the electrostatic forces are insignificant compared with the pressure load. For intermediate voltage, the electrostatic forces have a notable influence. In the region close to collapse of the structure, the influence becomes significant enough to cause dependence stronger than exponential and finally the contact occurs. Considering the relation between the distortion and the bias voltage, the working voltage has to be restricted to the linear region. The circular corrugated diaphragms can benefit from its upper offset for greater bias voltage. In our simulations, the upper limit of the linear range is about 60% of the pull in voltage.

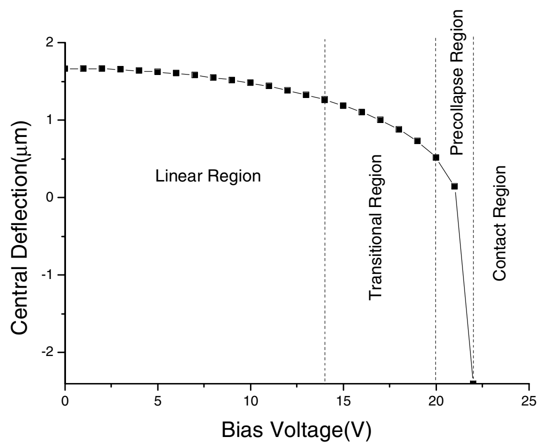

Figure 5. *The relation between central deflection and the bias voltage*

MEASUREMENT AND RESULTS

Each miniature microphone occupies a die area about 1.5 $\times$1.5mm^2, it is calculated that a 4-inch wafer can hold 7000 such miniature microphones. The batch fabrication at low cost would bring great profit. Figure 6-7 show the SEM photos of a miniature microphone and the close up of the corrugations.

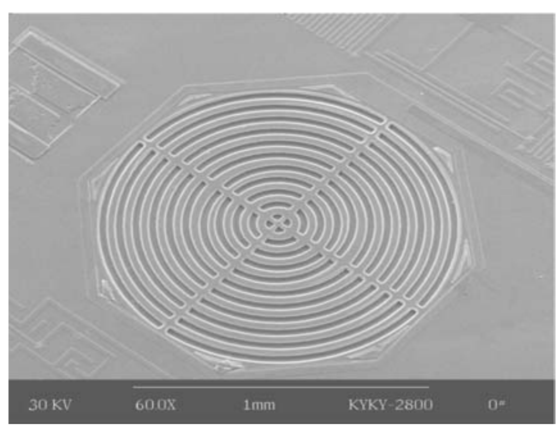

Figure 6. *SEM of a miniature microphone*

To avoid the nonlinear effects such as harmonic distortion, the bias voltage should be in the linear region. A working voltage of 14V is chosen for maximal sensitivity.

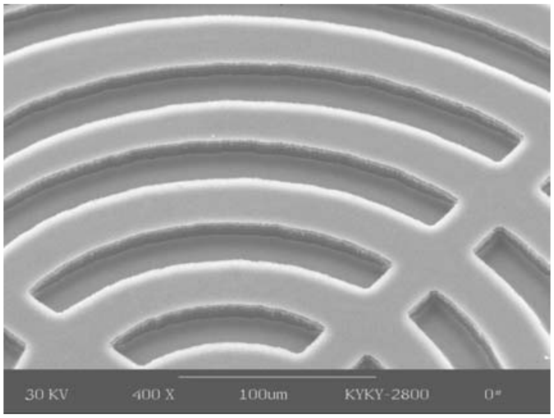

Figure 7. *SEM close up of the corrugations*

Wafer-level measurement was carried out using a Norsonic 840 real time analyzer. The wafer was supported on a specially designed clamp with a low noise amplifier encapsulated in a miniature metal tube near the probe. Since electrodes are located on the front side of the wafer, the whole setup has to be placed in a free sound field. The measurement result is shown in Figure 8. The open-circuit sensitivity is three times larger than the squared types[4]. The frequency response is flat upto 15KHz, which can be further improved by dedicate package or adjusting the design parameters[11].

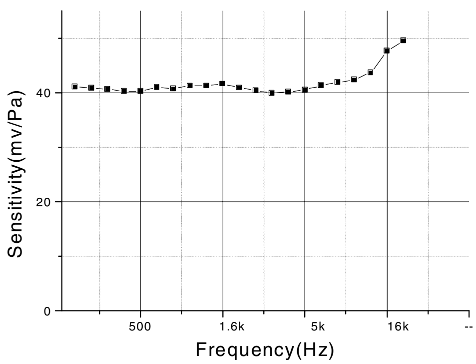

Figure 8. *Acoustical frequency response*

CONCLUSION

For the first time, a novel single-chip condenser miniature microphone with a circular corrugated diaphragm for residual stress releasing has been proposed, fabricated and tested. An electrostatic-structural coupling FEA was performed for design optimization. Both the simulation and the measurement results show that the sensitivities of circular corrugated diaphragms are several times larger than the square types. A sensitivity of 40mv/Pa up to 15KHz has been achieved under a low bias voltage of 14V, which is believed to fulfill most requirements.

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